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14. ABSTRACT

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Advanced Sensors for Airborne Magnetic Measurements

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ABSTRACT

Numerous ground tests and platform tests were conducted to evaluate platform integration issues and the performance of the POLATOMIC 2000 magnetometer, a laser-pumped helium-4 total magnetic field sensor. These results are compared with those from lamp-pumped helium-4 magnetometers, the AN/ASQ-208 and the AN/ASQ-81. The sensitivity of the digital AN/ASQ-208 magnetometer is 3 pT/√Hz from dc to 216 Hz; and, the analog AN/ASQ-81 has a slightly higher noise floor. The POLATOMIC 2000 noise floor is less than 0.3 pT/√Hz. For airborne measurements, the sensor noise is not usually the limiting noise. In the magnetic anomaly detection (MAD) band (0.04 Hz to 0.5 Hz), for example, substantial reduction of platform and environmental noise is necessary. Important sources of noise are geology, geomagnetic, platform, gradient, and wave. In order to reduce the effect of these noise sources, ancillary sensors are used in conjunction with noise models. These sensors are fluxgate magnetometers, accelerometers, and a low-noise C-code GPS. The performance of the POLATOMIC 2000 is described, as is the platform integration. Results of ground tests and flight tests are summarized, and the noise models and the effectiveness of the ancillary sensors for ambient and platform noise reduction are discussed.

1. INTRODUCTION

A new magnetometer (the POLATOMIC 2000 or P-2000) has been developed with US Navy support. A photograph of the laser-pumped helium-4 magnetometer system is shown in Figure 1. The magnetometer is shock mounted within an AN/ASQ-208 canister that fits within the designated space of the P-3 tail boom. Each P-2000 magnetometer has two helium cells that are about 1 foot apart. In the dual-cell magnetometer mode, the magnetic field at each cell is determined and summed and the noises are subtracted. When the dual-cell magnetometer is operated in the gradient mode, the signals from the two cells are subtracted from each other. Under these conditions, the noise and the signal are greatly diminished. The performance of the highly sensitive wide-band gradiometer is being evaluated for platform use. The gradiometer noise rejection is better than the magnetometer noise rejection, and the high sample rate reduces aliasing noise. The gradiometer performance is not optimized unless both circular polarizers provide the same polarization (right or left handed) to the helium cells; for the dual-cell magnetometer the polarization states are opposite. When only one cell from each of the P-2000 systems is used as a magnetometer, none of the system noises are cancelled, and the noise floor increases by about 10 dB. The magnetometer, operating in the dual mode, has a nominal sensitivity of 0.3 pT/√Hz; this is 10 times as sensitive as the

AN/ASQ-208 and about 30 times as sensitive as the AN/ASQ-81. Field tests at Polatomic, Inc. and US Navy ground tests have verified this sensitivity. The ground tests were used in part to resolve the platform integration issues. The ground tests included mounting and operating the P-2000 in the P-3 tail boom. One purpose of the ground tests was to get a measurement of the magnetic noise of the P-3 as seen by the new sensor. It was anticipated that some of the noise would be internal to the sensor, and some would be platform and environmental. Some of the internal noise would not have been apparent in the field tests at Polatomic because these tests were conducted in a more benign environment. Accordingly, it was planned to perform two similar sets of tests, one with the AN/ASQ-208 and one with the P-2000. The AN/ASQ-208 test acted as a baseline, to the extent that it could, for the more sensitive P-2000 magnetometer. Subsequently, flight tests of the AN/ASQ-208 and the P-2000 were conducted.
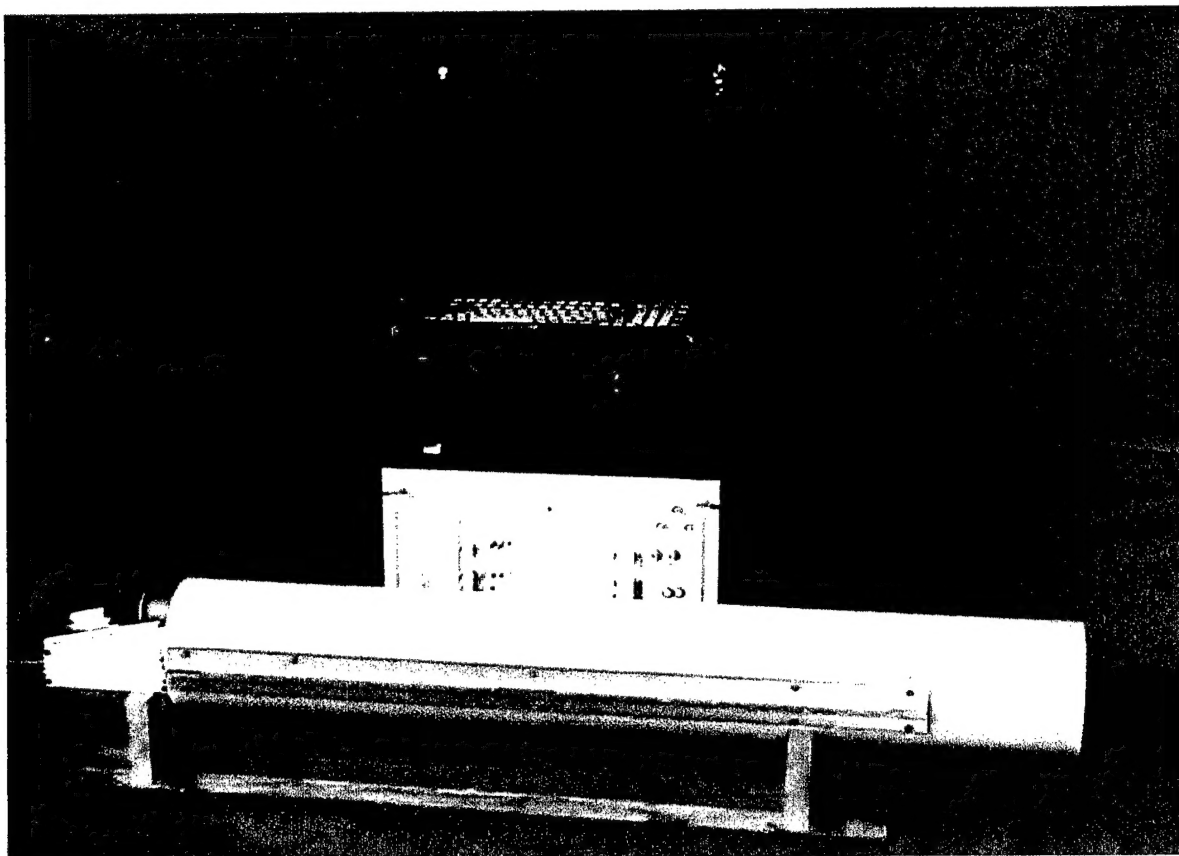

Figure 1. The POLATOMIC 2000 laser-pumped magnetometer system is shown.

2. DESCRIPTION OF THE POLATOMIC 2000 MAGNETOMETER/GRADIOMETER

Operation of the basic sensing element depends on the light-absorption properties of metastable helium atoms subjected to optical pumping and resonant radio frequency (H_1) radiation. The basic sensing elements are shown in Figure 2.

The optical pumping radiation source in the laser magnetometer is a distributed Bragg reflecting (DBR) diode laser (DL). The diode is electronically controlled and emits light at the wavelength required to optically pump the helium atoms inside the glass helium cell. Before the light enters the cell it is circularly polarized. The light travels through the helium cell to the infrared (IR) detector. A portion of the light is absorbed in the helium cell. The IR detector converts the light energy to an electronic signal and phase information contained in the signal is detected and sent to the digital oscillator. The RF output from the oscillator is used to drive a coil at 90 degrees to the light path and located near the helium cell. A low-frequency modulation of the RF produces an error signal at the modulation frequency, which is used to lock the resonance control loop. Resonance is obtained when maximum light is absorbed in the cell. The Larmor frequency is directly proportional to the applied magnetic field and is given by:

$$f_0 = g\, H_0,$$

where

H_0 = magnetic field in nanoTesla
g = gyromagnetic ratio of helium atom
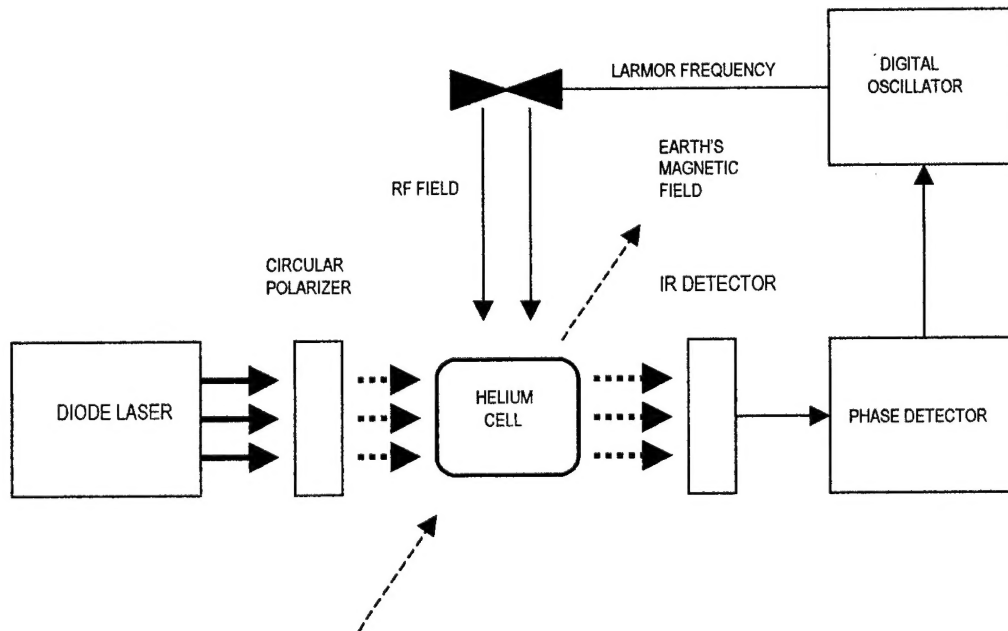$\quad$ = 28.0235 Hz/nT

Figure 2. The basic sensing elements of the laser-pumped magnetometer are shown.

Performance Characteristics

Range   22,302 to 78,058 nanoTesla (nT)
Resolution 83.1×10^{-6} nT
Noise Level   0.3 picoTesla (pT)/$\sqrt{Hz}$ (0.5 to 50 Hz)

A spectral density (SD) plot of the P-2000 gradiometer is shown in Figure 3. The upper curve is actually 2 spectra, one from each cell. The lower curve is the difference in the magnetic field at each cell, that is, the gradiometer spectrum. Note that the gradiometer noise floor is about 0.2 pT/$\sqrt{Hz}$ down to below 0.1 Hz. At the lower frequencies, there is some residue. Note the significant amount of ambient noise reduction across the entire band.
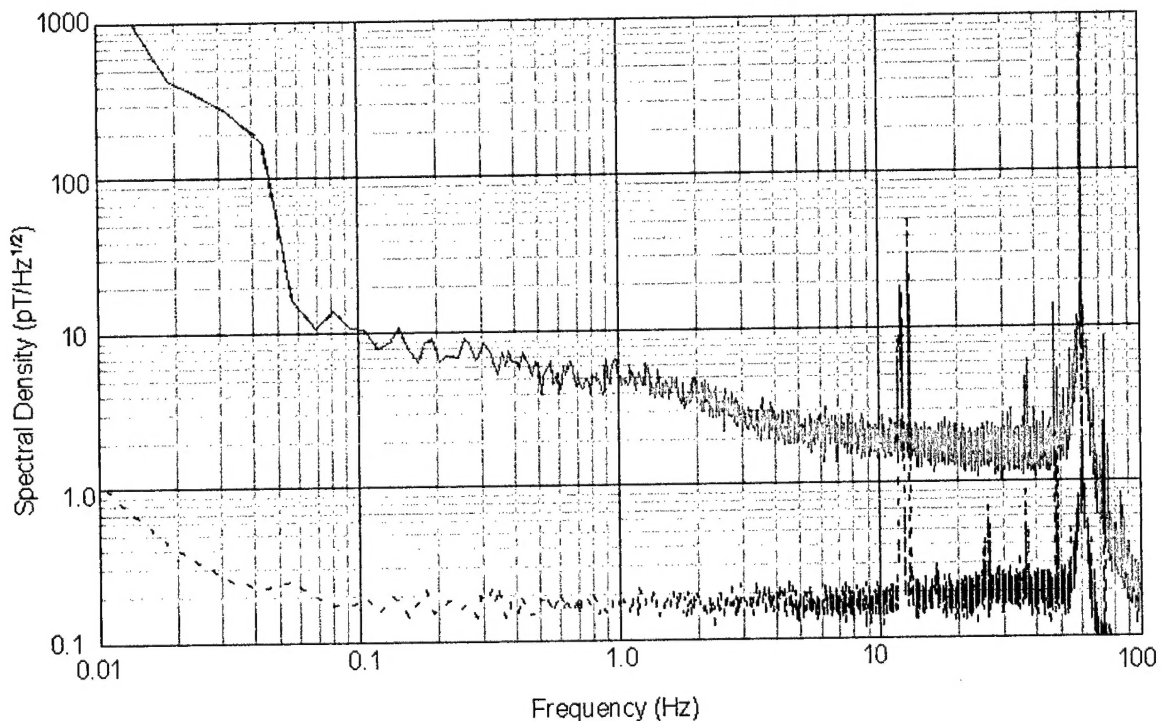
Figure 3. The spectrum from each cell and the difference spectrum are shown in this 43-minute spectral density plot. The upper two curves are largely coincident.

3. NOISES, NOISE REDUCTIONS, AND RELATED SENSORS

A study of the platform and ambient noises was performed. This study predicted the requirements for the ancillary sensors to reduce the noises to the P-2000 magnetometer noise floor in various bands. The results of that study and several recent studies are given in the following paragraph.

Optimal platform noise compensation coefficients are derived on dedicated maneuver data. Compensation coefficients derived from non-maneuver data do not work nearly as well. One of the principal contributors to the platform noise is the L x dL eddy current term. The analysis showed that the existing vector magnetometer does not have sufficient resolution to reduce platform noise, and, in particular, the L x dL term to the 0.3-pT/√Hz level. A factor of ten improvement in resolution is required of the vector magnetometers to reduce platform noise to the 0.3 pT/√Hz level. Platform motion in the clear air vertical electric field of the earth was examined. This motion produces magnetic fields at the magnetometer position that are too small by orders of magnitude to be of importance. From aircraft data for straight and level flights, it is observed that buffeting in low-gradient fields does not appear to be a significant noise source at higher frequencies, but it is in the MAD band. The NovAtel GPS with the University of Calgary software (C^3NAV) will be adequate for low-frequency buffeting noise reduction in low-gradient fields. A 1-mg accelerometer is required to measure small vibrations and buffets in high-gradient fields. A 1-mg accelerometer was bonded to the total field magnetometer to measure the magnetometer vibrations while residing in the tail boom. Measurements were made under various flight conditions to quantify the magnetometer displacement. To keep transient noise to a minimum, it is recommended that no equipment be turned on or off during the magnetic data collections. The transients associated with this equipment switching will be removed in post-processing.

In the previous noise reduction studies, a strong correlation was seen between one of the fluxgate magnetometers and the total field magnetometer for several of the narrow lines. The 17-Hz line, which appears in many spectra, has been identified as a magnetic line from the P-3 engines. It is not vibration related. Corona noise does not appear to be a problem; however, it has been found that the P-3 engines charge the platform in clear air. It may be necessary to instrument the static wicks with current monitors. Microphonic noise within the sensor does not appear to be part of the sensor noise spectrum, although there are electronic lines. It is possible to reduce both atmospheric and ionospheric noise by using a reference sensor and by using the polarization properties of the laser-pumped magnetometer. This has been done in the field tests and the results are reported in this paper. Either blanking or limiting can be used to reduce local lightning noise. Ocean swell noise is potentially a problem; it may be reduced by flying higher or frequency shifted by changing heading. The time-varying electric field under storm clouds does not appear to present a magnetic noise problem. The magnetic noise associated with the spatially-varying electric field does not appear to be significant.

In many geographical areas, the in-band geology noise can be a substantial noise depending on the frequency band of interest. Buffeting in the geology gradient will need to be addressed by correlating displacements determined from the accelerometer measurements with the total field variations. The noise from buffeting in the core gradient field is reduced through the IGRF model and the displacements determined by the GPS and the accelerometer. Preliminary data noise tests have shown that glitches in the data of various types can produce significant noise in the

PSDs. Therefore, glitches in the data that are larger than a predetermined level will be removed in post-processing. Control surface noise has been determined and is reported here.

4. DATA ACQUISITION SYSTEM

The details of the data acquisition system are given in Reference 1. The data acquisition system must be able to record and time tag data from the total field magnetometers, the fluxgate magnetometers, the accelerometer, the aircraft sensors, and the GPS. The POLATOMIC 2000 magnetometer sensitivity is between 0.1 and 0.3 pT/√Hz; and it will track magnetic fields to above 70,000 nT; the earth's field is nominally about 50,000 nT. The P-2000 resolution is about 1 part in 5×10^8 (29-bit A/D); and, it is recorded at 432 samples per second. The ASQ-208 is about ten times less sensitive than the P-2000; so, the resolution is about 1 part in 5×10^7 (26-bit A/D). For the Billingsley vector (fluxgate) magnetometer, the required sensitivity is 0.1 nT/√Hz; this fluxgate is actually about ten times more sensitive than this. The measured field may be in the plus or minus direction; this adds another factor of two to the resolution. So, the resolution of the Billingsley fluxgate is recorded at about 1 part in two million (~21-bit A/D). The sample rate is the same for all three magnetometers. The accelerometer resolution is better than 0.1 mg. This is sufficient to resolve vibration and buffeting noise at higher frequencies. The upper bound of the accelerometer is about 5 g. The resolution is about 1 part in 10,000. The accelerometer is also sampled at 432 Hz. The NovAtel position data for determining position, buffeting, and separation are recorded at 4 Hz. Roll, pitch and true heading data from the aircraft gyros are recorded at 8 Hz. All of this data must be time tagged for post processing. A timing test was required to determine the small time delays associated with the different data paths. The timing test allows precise data alignment for noise removal. The system must have the speed to record the data from all of the sensors and the capacity to store all of the data collected during a ten-hour flight.

The VME-based data collection unit has been designed to collect data from the AN/ASQ-208 Digital MAD System and the POLATOMIC 2000 Laser Magnetometer System. It can collect data from either of these two magnetometer systems individually or simultaneously when operated in a ground test configuration. The VME collection system records the data from each sensor on a removable hard drive. The sample rates for the data are as follows:

AN/ASQ-208	8 & 432 Hz
P-2000 Laser Magnetometer	8 & 432 Hz
Vector Magnetometer (TFM100G2)	432 Hz
Tri-Axial Accelerometer (PCB356B08)	432 Hz
NovAtel GPS	4 Hz
Roll, Pitch, and True Heading	8 Hz

Some additional characteristics of the data collection system are as follows. It is capable of displaying a subset of the sensor suite data in real time. For example, all three vector magnetometer axes, or all three accelerometer axes, or both P-2000 magnetometer cells may be displayed. It is also capable of the simultaneous display of raw and filtered total field data. The normal MAD band pass filters are available for viewing filtered data. Auto-scaling, as well as preset scale factors are selectable. Various running averages are available. The display is able to capture and hold data segments. And, running PSDs of the data are available to view the signals in near real time.

5. GROUND TESTS

Introduction

The ground tests were conducted at the Naval Air Station in Brunswick, Maine. The ground tests consisted of making dual magnetometer measurements at a remote site, surveying the aircraft apron site for the aircraft measurements, and making measurements with the P-2000 and the ASQ-208 magnetometers aboard the P-3. The cables from the tail boom sensors were run out of a boom access door, which was secured with green cloth tape. The cables were taped along the fuselage, and run through the free-fall chute to their respective pieces of equipment that were located in the P-3 galley. The aircraft did not have to be modified for these ground tests; however, for the flight tests, the aircraft had to be rewired to accommodate the new sensors and the data acquisition system. A concern for the aircraft tests is the value of the ambient gradient field at the magnetometer. The N-S and E-W gradients are measured by the aircraft P-2000 gradiometer. It should be remembered that these fields include the aircraft gradient fields as well. From earlier platform survey measurements, the magnitude of the horizontal gradients from the P-3 was measured to be in the range 0.03 nT/foot to 0.15 nT/foot. The longitudinal horizontal values from these tests are 1.35 nT/foot on the north heading and 0.59 nT/foot on the west heading. Most of the measured gradient field is due to the enhanced ambient field from the steel-reinforcing rod in the concrete apron.

P-2000 Dual-Cell Magnetometer Ground Test

The data for Figure 4 were acquired with the P-2000 sensors closely spaced (about 30 feet apart) on a baseball field in a remote area of the Brunswick NAS. This spot was recommended as being relatively free from power lines and traffic. In Figure 4 are shown the data for the pair of P-2000 magnetometers operating in the dual-cell mode. Again, in the dual-cell mode, the signals from the two magnetometer cells that are about 12 inches apart are summed and laser noise is cancelled. The uppermost plot in Figure 4 includes three SDs. The sample rate for these SDs is 432 Hz and the time record size is 32768. The time record is then 32768/432 = 76 s, and the frequency resolution is 0.013 Hz. Frequency bin averaging is used, and in this case we have 8 x 0.013 = 0.105 Hz, which is the

spectral resolution. The data was windowed with a Hanning window. The blue trace is the aircraft sensor (that is, the sensor that will ultimately be mounted into the tail boom), the green trace is the reference sensor, and the red trace is the difference plot. As can be observed in this SD plot, the atmospheric noise is very low. It is below 1 pT/√Hz from below 1 Hz to 40 Hz except for a few peaks. The subtraction of the reference sensor brings the noise down to below 0.3 pT/√Hz at higher frequencies. The 12-Hz line in the SDs is a beat between 432 Hz and 7 x 60 Hz. The low-noise operation of the magnetometers in the dual-cell mode is demonstrated. The middle plots (green and blue) display the time dependence of
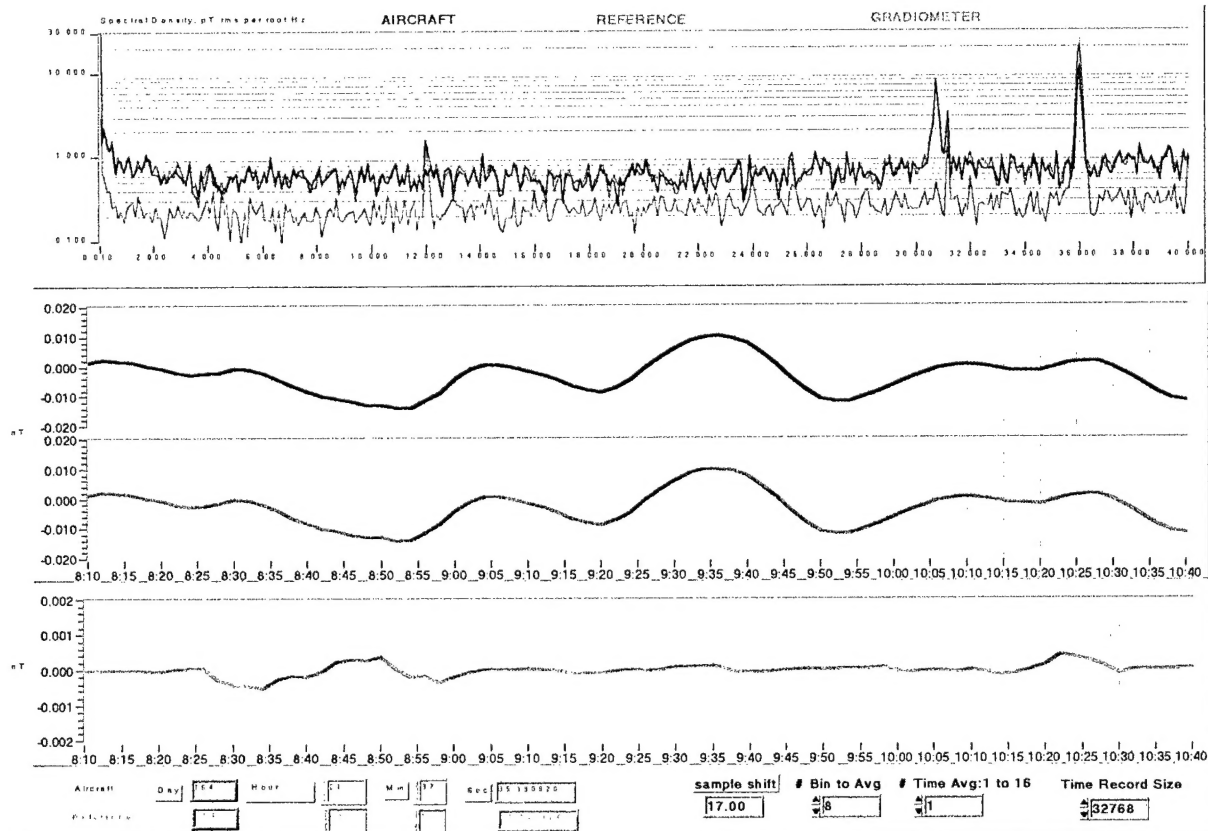

Figure 4. Background noise data taken with a pair of P-2000 magnetometers operating in the dual-cell mode are displayed.

the processed output from each sensor. These plots show the processed low-frequency geomagnetic noise. The noise is relatively low here. The time is in minutes and seconds, and the vertical scale on the left is in nT/s. These time plots are running 8-second averages that are updated every 0.25 second. Adjacent points are subtracted and the difference is displayed. This process removes the large variations seen in the raw data from which the PSDs are derived. The red plot at the bottom of the figure is the difference between the green and blue plot or the second difference. The vertical scale is again in nT/second. Note that the full-scale value in this figure is 2 pT/s, and the noise is very low.

In Figure 5 are shown SDs of data taken several hours later by the dual-cell magnetometers. A log scale is used for frequency; this enables expansion of the low-frequency region. We observe good geomagnetic noise cancellation to below 0.1 Hz. The first difference plot shows the geomagnetic noise to have increased over Figure 4. Note in the bottom plot that the difference noise is a few tenths of a pT/s.

From these measurements, the P-2000 dual-cell magnetometer system has a noise floor at or below 0.3 pT/√Hz in the band 0.1 to 50 Hz.
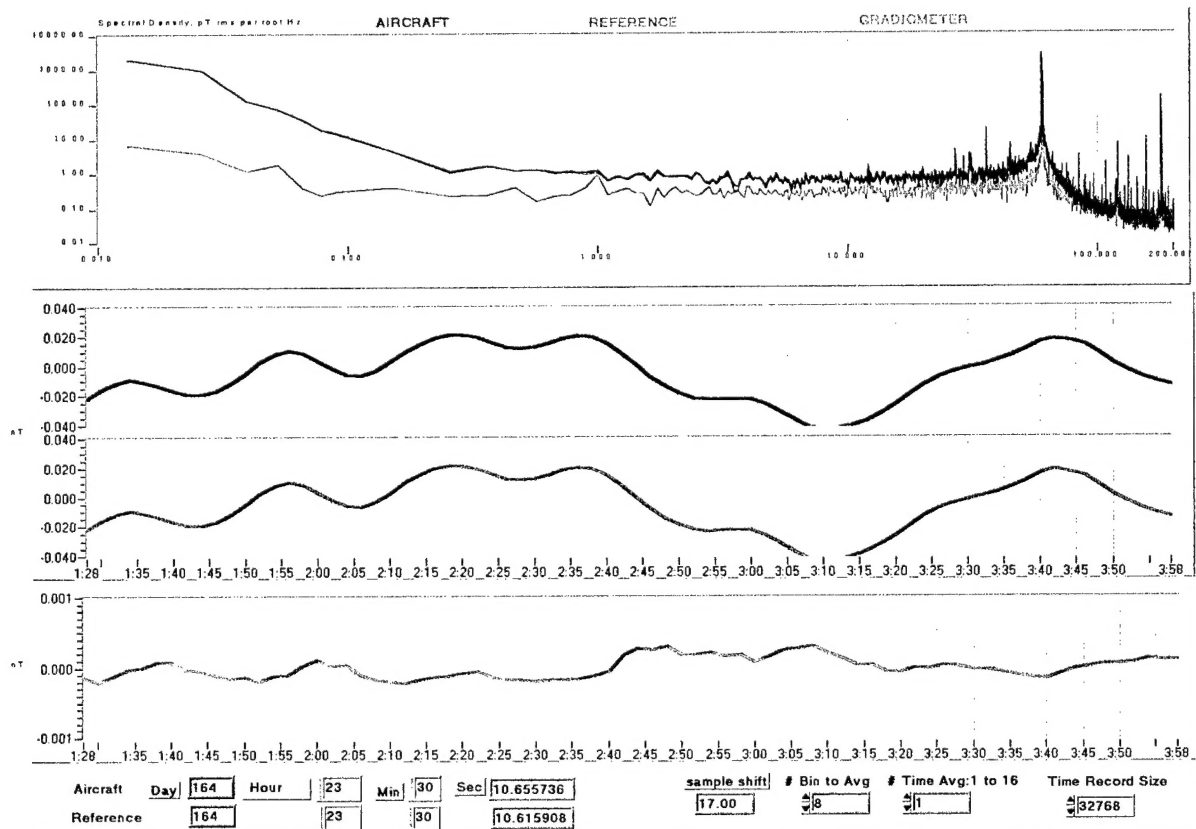

Figure 5. Background noise data taken with a pair of P-2000 magnetometers operating in the dual-cell mode are displayed. A log frequency plot is used here to expand the low frequency region.

P-2000 Gradiometer

Single system gradiometer data was acquired at the ball field as well. For this case, each cell operated near the 1 pT/√Hz level because of the ambient noise. The gradiometer noise was at the 0.5 to 0.7-pT/√Hz level. The gradiometer noise may be further reduced by using the same polarization for the laser light in each cell. This requires the rotation of a ¼-wave plate internal to the magnetometer. This was not done for these tests. However, the data shown in Figure 3 display the true gradiometer noise floor. The data for this 43-minute spectral density plot were taken

at Polatomic, Inc. It may be observed from this data that the gradiometer noise floor is near 0.2 pT/√Hz from below 0.1 Hz to 50 Hz except for a few narrow lines of different origins.

Aircraft Ground Tests

The aircraft ground tests were conducted using the auxiliary power unit (APU) to power all of the aircraft equipment. During all of the aircraft tests, especially without the engines running, there was a fair amount of activity around the aircraft. This activity included Navy personnel checking the plane, various personnel coming aboard, leaving, and walking forward and aft, and vehicles driving around. All of these activities create signals (noise). Some of the noise arises from the motion of the magnetometer in the gradient field. Based on the 1- to 2-Hz magnetometer displacements as determined from the accelerometer data and the associated magnetic fields, the vertical gradients are in the 1- to 1.5-nT/ft range. The horizontal gradients as stated before are about 1 nT/foot at the tail boom. A displacement of 0.004 inches creates a noise at the 0.3-pT level. Motion in the gradient field is a significant noise source for these ground tests. The ambient gradient fields for this test are about 100 times larger than the core gradient field of the earth. And, significant motions within the aft cabin were observed during these tests, especially during the engine power portions. In fact, there was more apparent motion than during flight. Because of this, motion noise dominates much of the ground-based platform noise data.

During the aircraft ground tests, both magnetometers were tested on both headings. Control surfaces were moved, and equipment was switched on and off. The tests were performed with the engines on and off and with the propellers in and out of synchronization. A ground station was set-up with a second P-2000, a GPS, and a data collection system; this equipment acted as a geomagnetic reference station. During these tests, the Polatomic magnetometers were run in both the gradiometer mode and in the dual-cell mode. Again, several ancillary sensors were also used during the ground test; these were a GPS antenna/receiver for time tagging and a 1-mg accelerometer for measuring vibrations.

Control Surface Noise

Each control surface (elevators, rudder, and the ailerons) was moved slowly from neutral to full up, back to neutral, to full down, and back to neutral. Regions of high magnetic moment in the control surfaces and their actuating mechanisms will cause magnetic signals during displacement. Both gradiometer and magnetometer data were taken during the time that the elevators were being moved up and down. The gradiometer data is lower in noise than the magnetometer data. The gradient field from the elevators is about 20 pT/foot peak-to-peak. We can convert the gradient field at the magnetometers to magnetic field by multiplying by the distance from the elevator to the gradiometer divided by three (~20 feet/3 = 6.6 feet). So, the magnetic field from the full motion of the elevators is about 130 pT. This value

agrees with the total field measurements. The gradient field from the rudder motion is in the 6 to 8 pT/foot range. Using the above formula and the appropriate distance, these gradients are associated with 40 to 50 pT magnetic fields. Again, this value is in agreement with the total field measurements. The aileron data show no associated magnetic gradient field. This is not surprising because of the large separation between the ailerons and the magnetometer. The aileron noise is not seen in the total field data as well. The above values will be greatly diminished during straight and level flight because of the small displacements.

Equipment Switching Noise

The cabin noise tests were conducted to make measurements of the noise produced by switching various aircraft components on and off. The items switched were the strobe lights, the windshield heater, the windshield deicer, the cabin lights, the VHF and UHF radio, the galley circuit breakers, tacan transmitter, and the HF transmitter. These items, when switched on and off, cause current changes in their respective circuits that in turn cause magnetic field changes at the magnetometer. The magnetic fields are aircraft orientation dependent. The time-dependent data were collected for the cabin noise tests with the aircraft on a northerly and westerly heading. Substantial changes in magnetic field were observed during the test period. The data were noise reduced by subtraction of the reference sensor and low-pass filtered at 50 Hz. There is a 50-pT positive step associated with the windshield heater and a negative 30-pT step associated with the deicer. There was a series of negative spikes (0.4 nT) due to the UHF radio, and small positive spikes (0.1 nT) due to the VHF radio. There were very large noise spikes (~ 1 nT) due to the HF transmitter.

Geomagnetic-Atmospheric Noise

There have been numerous studies of the ionospheric/magnetospheric (often called geomagnetic) noise below 0.1 Hz and the atmospheric magnetic noise above 10 Hz. By comparison, there are very few studies of the geomagnetic-atmospheric (G-A) noise between these two frequencies. Much of the data presented here applies to this interim region. A summary (Reference 2) of the characteristics of the G-A noise is as follows. There is some variability in the G-A noise. It is slightly larger in summer than in winter, slightly larger during the day than at night, and slightly larger with higher A_p indices. For the lower frequencies, the G-A noise is higher at higher latitudes. We don't have sufficient data to know how the G-A noise varies across the band with latitude. The vertical component depends strongly on location. The following numbers that have been taken from the available literature are used as ballpark figures. At the first Schumann resonance (near 8 Hz), the horizontal noise is about 1 pT/√Hz. Almost all of the data show a shallow minimum near 5 Hz. The horizontal noise at 1 Hz is about 3 pT/√Hz. And, the horizontal G-A noise near 0.5 Hz is in the range 6 to 10 pT/√Hz. It appears that there are no long-term differences between N-S and E-W measurements, although there are short-

term differences. The vertical noise is quite variable; this is usually attributed to the local geology. It appears that the vertical G-A noise will be at least a factor of 10 smaller than the horizontal noise in an area where the conductivity is uniform, like over the ocean.

The ground tests were conducted at Brunswick, ME (near 44°N, 70°W and low altitude). From IGRF-95, the following magnetic field parameters are given for this location, (north – 17,841 nT, east - -5,545 nT, z (down) – 51,387 nT, total magnetic field – 54,678 nT, horizontal magnetic field – 18,683 nT, inclination - 70° down, declination is -17.3°). If we assume that the noise band of interest is near 1 Hz, then the total G-A noise is about 3 pT. Additionally, we assume that the noise is equal along both horizontal axes, and it is zero along the vertical axis. These assumptions are consistent with a survey of the literature. However, at any given time, the G-A noise may be stronger along one of the horizontal axes. Because the E-W noise component is orthogonal to the earth's field, none of the E-W noise is detected. And, only the N-S component that is along the earth's field is detected. So, the detected G-A noise component at 1 Hz will be equal to

$$(3/\sqrt{2}) \cos 70° = 0.73 \text{ pT}.$$

We observe from the above example that there is some G-A noise rejection by the total field magnetometer.

6. FLIGHT TESTS

The POLATOMIC 2000 magnetometer system, the ancillary sensors and the data collection system were installed onto a P-3 at Patuxent River, MD. Preliminary ground tests verified the operation of all of the equipment. The first flight test of the P-2000 system was conducted on March 20, 2001. This flight consisted of dedicated maneuvers on cardinal headings, long straight flight legs on cardinal headings, standard rate turns, and both magnetometer and gradiometer data collections. All of the equipment worked as planned. Data was collected for the entire flight. However, there are several noise sources on this platform that raise the noise floor in different bands above those observed on other P-3 platforms. The current platform noise floor, which is not correlated with maneuvers and buffeting, prohibits effective noise reduction. The focus of the current effort is to identify and reduce these adventitious platform noise sources.

7.CONCLUSIONS

The POLATOMIC 2000 magnetometer/gradiometer and ancillary sensors have been tested in a series of ground tests and flight tests. From the ground tests, the P-2000 magnetometer has a noise floor of 0.3 pT/$\sqrt{\text{Hz}}$ and the gradiometer noise floor is about 0.2 pT/$\sqrt{\text{Hz}}$. The integration of the P-2000 System into the P-3 platform was successful. All of the sensors and the data acquisition system operated as planned. The increased sensitivity and noise rejection of the P-2000

gradiometer make it a strong candidate for airborne utilization. Geomagnetic-atmospheric noise reduction was demonstrated through the use of a reference sensor. Initial flight tests have shown significant platform noise of unidentified origin.

8. ACKNOWLEDGMENTS

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